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Energy and Buildings 39 (2007) 954–961
ENERGY and BUILDINGS
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# Facade design optimization for naturally ventilated residential buildings in Singapore

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Received 21 July 2006; received in revised form 30 August 2006; accepted 17 October 2006

**Abstract**

Parametric studies of facade designs for naturally ventilated residential buildings in Singapore were carried out to optimize facade designs for better indoor thermal comfort and energy saving. Two criteria regarding indoor thermal comfort for naturally ventilated residential buildings are used in this study. To avoid the perception of thermal asymmetry, temperature difference between mean radiant temperature and indoor ambient air temperature should be less than 2 °C [F.A. Chrenko, Heated ceilings and comfort. J. Inst. Heat. Ventilating Eng. 20 (1953) 375–396; F.A. Chrenko, Heated ceilings and comfort. J. Inst. Heat. Ventilating Eng. 21 (1953) 145–154]. Thermal comfort regression model for naturally ventilated residential buildings in Singapore was used to evaluate various facade designs either. Facade design parameters: *U*-values, orientations, WWR (window to wall ratio) and shading device lengths are considered in the investigation. The building simulation results for a typical residential building in Singapore indicated that the *U*-value of facade materials for north and south orientations should be less than 2.5 W/m$^2$ K and the *U*-value of facade materials for north and south orientations should be less than 2 W/m$^2$ K. From the coupled simulation results, it was found that the optimum window to wall ratio is equal to 0.24. Optimum facade designs and thermal comfort indexes are summarized for naturally ventilated residential buildings in Singapore.


*Keywords:* Natural ventilation; Facade design; Thermal comfort; Simulation

## 1. Introduction

There is a growing interest in the application of natural ventilation in buildings due to the energy, indoor air quality and environmental problems associated with mechanically ventilated buildings. Various mechanical systems including heating, ventilation and air-conditioning (HVAC) systems in residential and office buildings contribute substantially to the energy consumption.

As the benefits of natural ventilation, including reducing operation costs, improving indoor air quality and providing satisfactory thermal comfort in certain climates, are recognized, passive cooling of houses using natural ventilation has become an attractive alternative to alleviate the associated problems with air-conditioned buildings. The concept of natural ventilation is well accepted and welcomed by people and designers in the world. Even in places with hot-humid climates, where air-conditioners are ordinary in both residential and commercial buildings, naturally ventilated buildings are not uncommon. For example, 86% of the people in Singapore live in HDB (Housing and Development Board) residential buildings, which are designed to be naturally ventilated.

Natural ventilation is difficult to design and control although the principle itself is not difficult to understand. The excessive amount of moisture in the air and intensive solar radiation makes many passive cooling design strategies difficult to implement in hot and humid regions. The success of a naturally ventilated building is decided by a good indoor climate, which influences its sustainability. The thermal performance of facade components plays an important role in determining heat gains into buildings which can determine the indoor environment, especially for buildings with low internal heat source such as residential buildings or schools. For this reason, naturally ventilated building design in hot-humid climates needs to pay more attention to orientations, shading devices, material selections, and window sizes. The study of heat gains through facade for naturally ventilated buildings is more critical than that for air-conditioned buildings since the amount of heat gain

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0378-7788/$ – see front matter 
doi:10.1016/j.enbuild.2006.10.011

is a significant factor influencing the indoor thermal comfort for naturally ventilated buildings. Ventilation is considered to be one of the effective means to achieve thermal comfort in naturally ventilated buildings. With the increase of air velocity, neutral temperature for thermal comfort can be increased. Another important factor that affects thermal comfort in naturally ventilated buildings is solar heat gain, which can be controlled by shading devices. Increasing window to wall ratios can improve ventilation and indoor air quality but increase solar heat gain as well and therefore, external shading devices become an important component to reduce solar heat gain, especially for large windows. The evaluation of thermal performance of facade designs in naturally ventilated buildings should been conducted in a comprehensive way and arbitrarily exaggerating the effects of one particular component and neglecting the effects of others would be biased. Thermal comfort is an effective criterion to integrate the various impacts of all these facade components on indoor thermal environment.

The significant effects of dynamic outdoor climate on indoor environment increase the complexity of natural ventilation. Although there are many research works carrying out on the impacts of facade components on energy consumptions in sealed mechanically ventilated buildings (e.g. [1–3]), the knowledge of facade designs in naturally ventilated building is deficient, especially for the hot-humid climate. Therefore, the optimization and comprehensive evaluation of the facade systems for naturally ventilated buildings are carried out for hot-humid climate based on thermal comfort criteria. This paper is based on the previous studies [4] to further investigate facade optimization with two facade design criteria and develop facade design guidelines for naturally ventilated residential buildings in Singapore.

## 2. *U*-value determination with building simulations

Thermal resistance of facade plays an important role in reducing solar heat gain and maintaining a good indoor thermal environment. The criteria that temperature difference between mean radiant temperature (MRT) and indoor ambient air temperature should be less than 2 °C [5] to avoid the perception of thermal asymmetry by occupants is adopted to evaluate the thermal performance of external wall with various *U*-values. The thermal impacts of *U*-value are mainly on indoor location nearby openings and the impacts of facade material properties on indoor averaged thermal environment (centre of the room) are relatively small. Actually, thermal impacts of *U*-values are most significant in indoor locations near the openings (within 200 mm distance from openings) and thus demands further investigation.

### 2.1. The simulated building

High rise residential building HDB274C model (Fig. 1) was built for the parametric studies on *U*-values by a series of TAS simulations (EDSL, UK [6]). TAS is a suite of software products, including TAS Building Designer, TAS system and TAS Ambiens to simulate the dynamic thermal performance of buildings and HVAC systems and trace the thermal state of the building through a series of hourly snapshots, with integrated zonal simulation of natural and forced airflow. A bedroom with one external wall at the 10th floor in the buildings is selected for the study.

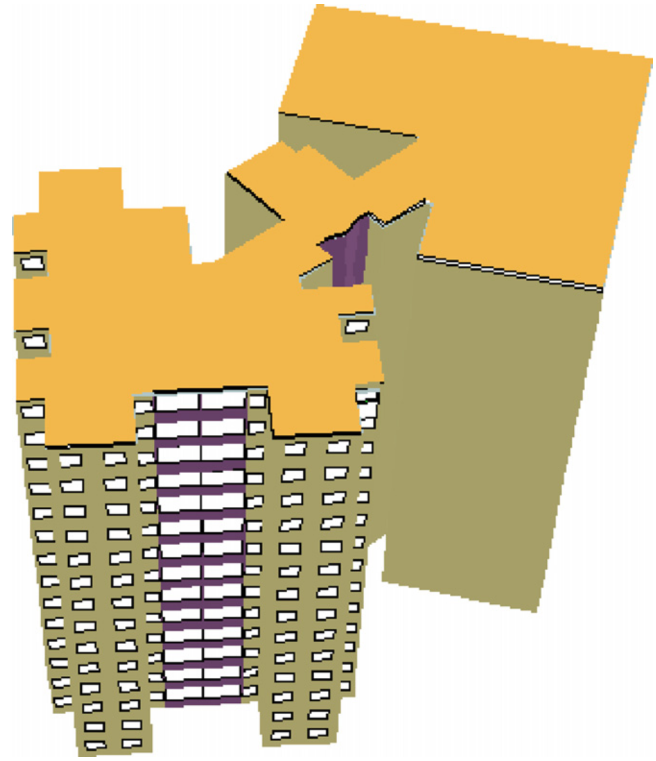

Fig. 1. HDB274C model in TAS simulation.

In this study, *U*-values ranged from 1.5 to 3.5 W/K m$^2$ at 0.5 intervals. The window size was made to vary from WWR = 0.1 to WWR = 0.4. Three orientations: north, east, west are investigated. The indoor ambient temperature and mean radiant temperature near the openings are affected by changing the *U*-value. In the simulation, the weather file 2001 was adopted. The hottest day in typical year 2001 for Singapore was selected for this study. The highest solar radiation was 979 W/m$^2$ and outdoor ambient temperature was 33.8 °C.

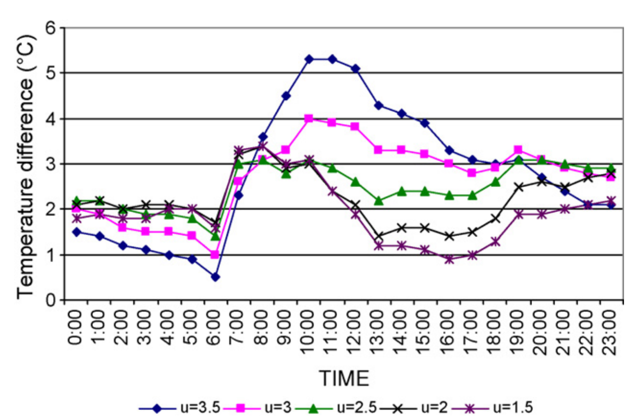


Fig. 2. Difference between mean radiant temperature and indoor ambient temperature (WWR = 0.1).

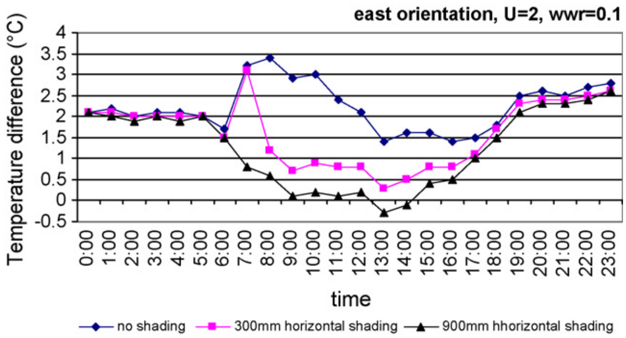


Fig. 3. Difference between mean radiant temperature and ambient temperature when the window shading device was adopted (WWR = 0.1).

### 2.2. East oriented external wall

The difference between MRT and ambient temperature ($\Delta T$) when WWR = 0.1 is illustrated in Fig. 2. When the $U$-value of external wall was kept below 2 W/m$^2$ K, the $\Delta T$ was less than 2 °C in most of the time except in the morning and late evening. In the late evening, since the ambient air temperature is low, it cannot be concluded that the indoor thermal comfort is not satisfied due to higher $\Delta T$ (>2 °C). In the morning, it is noticed that even the $U$-value of external wall is 1.5 W/m$^2$ K, the $\Delta T$ is still as high as 3.5. Thus, window shading device is added to reduce the temperature difference between MRT and ambient temperature.

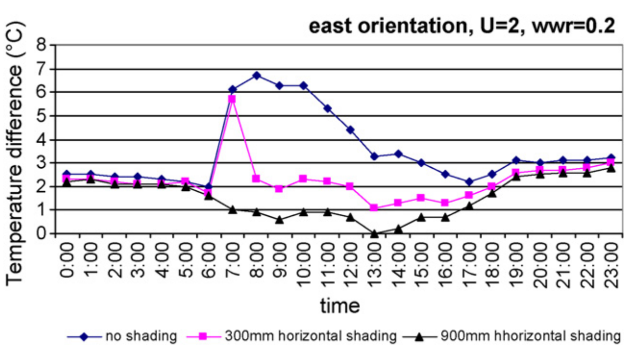


Fig. 4. Difference between mean radiant temperature and ambient temperature when the window shading device was adopted (WWR = 0.2).

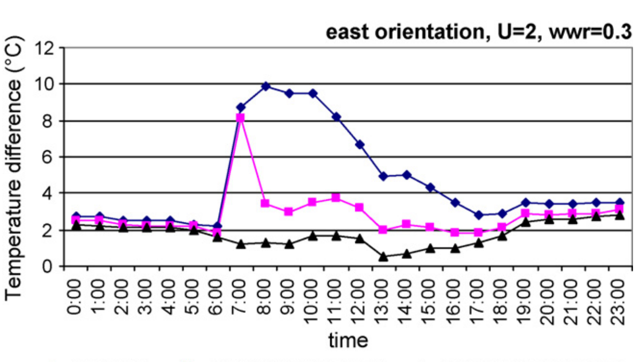


Fig. 5. Difference between mean radiant temperature and ambient temperature when the window shading device was adopted (WWR = 0.3).

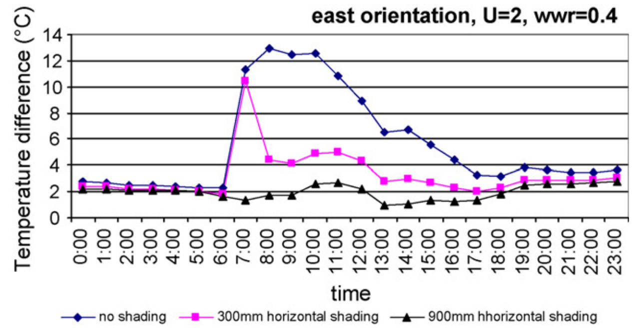


Fig. 6. Difference between mean radiant temperature and ambient temperature when the window shading device was adopted (WWR = 0.4).

Fig. 3 shows the $\Delta T$ when the $U$-value of external wall is 2 W/m$^2$ K and the window shading devices are applied for the window with a WWR value of 0.1. It can be seen using the 300 mm horizontal window shading device dramatically decreases the $\Delta T$ comparing with the situation that there is no shading device. Hence, the 2 W/m$^2$ K is the acceptable $U$-value for east oriented external wall with a WWR value of 0.1 and the 300 mm horizontal shading device has to be used at the same time.

Figs. 4–6 show the effect of window shading device when the $U$-value of east external wall is 2 W/m$^2$ K and the window size is changed from WWR = 0.2 to WWR = 0.4. From Fig. 4, it can be observed that when the WWR is increased from 0.1 to 0.2, the $\Delta T$ can be controlled under 2 °C by the adoption $U$ = 2 W/m$^2$ K external wall and 300 mm horizontal shading for the window. Fig. 5 shows that when the window size is increased to WWR = 0.3, the 900 mm shading device can provide good effect. However, from Fig. 6, it can be observed that when the WWR is 0.4, $\Delta T$ exceeds 2 °C slightly during the morning, even though the 900 mm shading device is adopted.

In conclusion, suitable $U$-value for east external wall is less than 2 W/m$^2$ K. Window shading device is necessary as long as there is window on the external wall. When the WWR is less than or equal 0.2, 300 mm horizontal shading is enough. When the WWR = 0.3, 900 mm horizontal shading can provide good effect. When the WWR is larger than 0.4, the indoor thermal comfort cannot be ensured in a good level during morning.

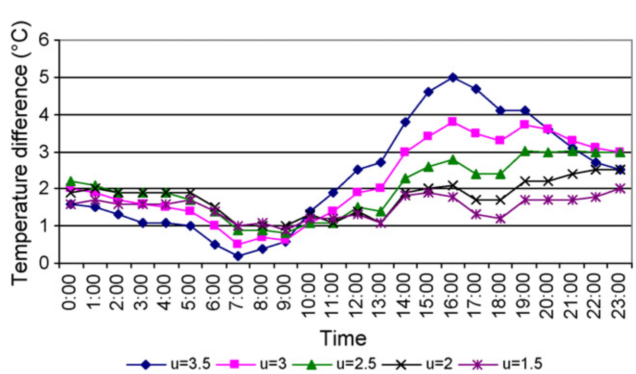


Fig. 7. Difference between mean radiant temperature and indoor ambient temperature (WWR = 0.1).

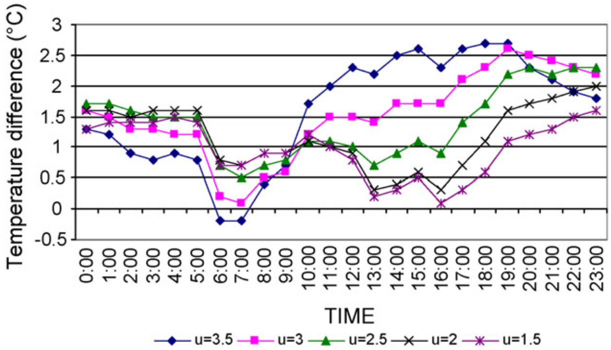


Fig. 8. Difference between mean radiant temperature and indoor ambient temperature (WWR = 0.1).

### 2.3. West oriented external wall

With the same approach, the difference between the indoor mean radiant temperature and ambient temperature ($\Delta T$) when WWR = 0.1 for west oriented wall were calculated. The results as shown in Fig. 7 indicate that when the $U$-value of west external wall is 2 W/m$^2$ K, $\Delta T$ is less than 2 °C during the whole day except in the late evening. Therefore, horizontal shading devices with various dimensions are added in to minimize temperature difference. When the $U$-value of west external wall is 2 W/m$^2$ K and WWR = 0.1, $\Delta T$ can be controlled under 2 °C during the entire day by using 300 mm horizontal window shading device. When the window size was increased to WWR = 0.2, 300 mm horizontal shading device still has good performance. When WWR is larger than or equal to 0.3, 900 mm horizontal shading device is necessary to avoid thermal asymmetry.

### 2.4. North oriented external wall

Similarly, for north oriented external wall, as illustrated in Fig. 8, when the $U$-value is 2.5 W/m$^2$ K and WWR = 0.2, $\Delta T$ is always below 2 °C before 7 p.m. Hence, 2.5 W/m$^2$ K is assumed as the suitable $U$-value for the north oriented external. When the window size was increased to WWR = 0.2, the $\Delta T$ exceeds 2 °C since late afternoon and thus window shading device is required. The simulation results indicate when the $U$-value of north external wall is 2.5 W/m$^2$ K and the WWR is less than 0.4, 300 mm horizontal shading device is enough to maintain a good indoor thermal comfort.

Since the solar radiation on north orientation is very similar with that on south orientation for equatorial regions, the results of suitable $U$-value and shading device performance which are obtain above are also available for south orientated facades.

## 3. Facade design parametric studies with coupled simulations

### 3.1. Coupled simulations

The above studies on facade materials showed that $U$-value for the east and west facing facade should be no more than 2 W/m$^2$ K and for north and south should be no more than 2.5 W/m$^2$ K to avoid the perception of asymmetry near openings. However, indoor air velocity, one of the significant parameters in thermal comfort for naturally ventilated buildings, cannot be accurately predicted and fully addressed by building simulation alone. Therefore, the impacts of window sizes on indoor air velocity cannot be accurately described by building simulations.

For more accurate prediction of indoor thermal environment for naturally ventilated buildings as building simulation assume the zone is well mixed, coupled simulations between building simulation (ESP-r) and indoor CFD simulation (FLUENT) were adopted in this parametric study. The developed coupling program between ESP-r and FLUENT for natural ventilation prediction can assess the performance of natural ventilation in whole buildings, as well as detailed thermal environmental information in some particular spaces, has been used for facade evaluations. The procedure of this coupling process, as shown in Fig. 9, is to obtain the internal surface temperature, pressure at the openings, which will be saved at data exchange interface. The boundary conditions will be automatically fed into indoor CFD simulation for a series of hours using the script program. With the aids of developed coupling program, coupled simulations between building simulations and computational fluid dynamics can quickly and accurately predict indoor

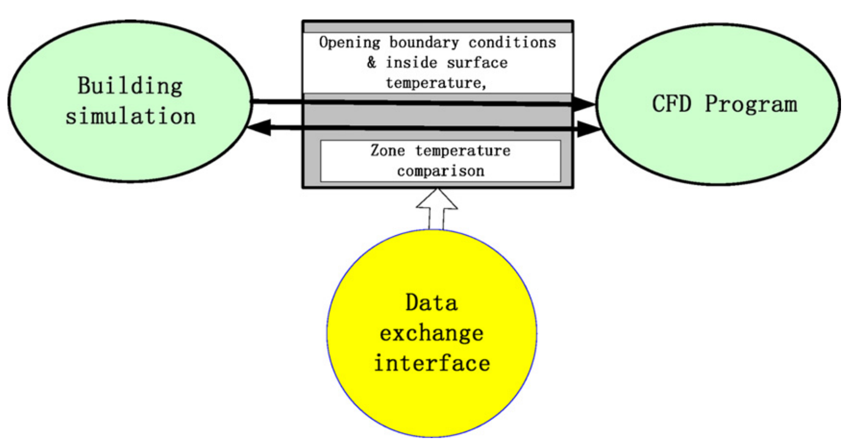


Fig. 9. The coupling strategy between building simulation and CFD.

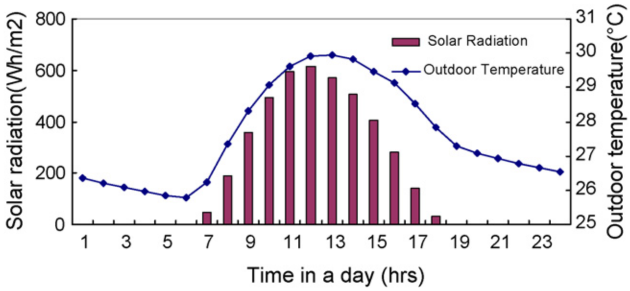


Fig. 10. Outdoor average temperature and solar radiation profile in the whole year.

thermal environment for long term or short term natural ventilation studies. The data exchange interface has been programmed to automatically implement the data exchange between the two programs. In this parametric study, three prominent facade design parameters, including orientations, window to wall ratios and shading device dimensions, are investigated by coupled simulations. Thermal comfort regression model (Eq. (1)) [7] for indoor environment is provided for evaluation of various facade designs based on the generated results:

$$\text{PMV} = -11.7853 + 0.4232 \times \text{Temp} - 0.57889V \quad (1)$$

where Temp indicates the indoor air temperature and $V$ refers to indoor air velocity measured at 1.2 m above the ground. The term PMV refers to the average (mean) response of a group exposed to a given climatic conditions rather than individual responses.

### 3.2. Typical weather data selection for parametric studies

In order to provide facade engineers or architects user-friendly tools to estimate the indoor thermal environment according to the particular designs, the typical weather conditions are used to build up indoor velocity charts, thermal comfort index charts for various facade designs are created using the year 2001 data. Typical-hour method is adopted to predict indoor thermal environment with various facade designs based on thermal comfort index on the aspects of window to wall ratios, shade devices and orientations. The procedures of choosing typical weather conditions (typical hours) are as follows:

(a) Hourly outdoor dry bulb temperature and solar radiation (shown in Fig. 10) in the typical year have been averaged based on the weather data.

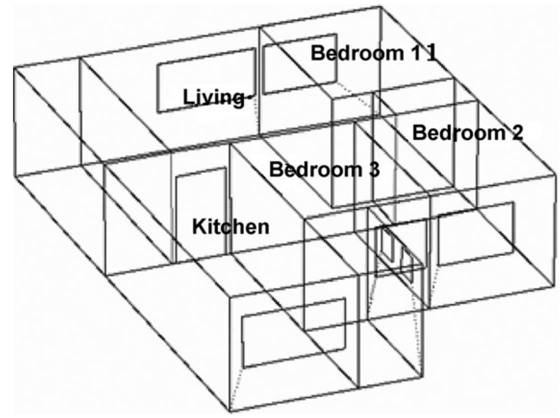


Fig. 11. The layout of the four-room HDB unit.

(b) In this typical averaged day, the peek values on outdoor dry bulb temperature and solar radiation appear at 12 o'clock. This outdoor dry bulb temperature and solar radiation pair is taken as the elements of typical weather conditions.
(c) The wind data are divided into 16 categories based on wind directions, in which 8 categories (see Table 1): N (north), S (south), W (west), E (east), NW (northwest), NE (northeast), SW (southwest), and SE (southeast) are selected for typical weather conditions. Year-averaged wind speeds in these eight directions are used as wind data in this study.
(d) Therefore, averaged wind data in eight wind directions combined with averaged outdoor dry bulb temperature and solar radiation pair are used for parametric facade design studies as typical weather conditions.

### 3.3. The simulated building

HDB building block601, west coast, is used in this parametric study. A typical living room in the HDB residential buildings on the sixth floor, which holds one external wall, is the targeted subject for the parametric study. The layout of the HDB unit is shown in Fig. 11. The living room has five openings: one window within the facade, one door connected with kitchen and the other three doors are connected with bedroom1, bedroom2 and bedroom3, respectively. The window and door connecting to the kitchen are assumed to be fully open and the other three doors connected with bedrooms are assumed to be close. The window within the facade in kitchen is assumed to be fully opened for 24 h.

In this parametric study, 48 cases were investigated for indoor thermal comfort. North, south, east and west orientations are investigated for the orientation parameter. Four WWR

Table 1
Averaged wind data in 16 wind directions in the typical year

| Wind direction | 0 (N) | 22.5 | 45 (NE) | 67.5 | 90 (E) | 112.5 | 135 (SE) | 157.5 |
|---|---|---|---|---|---|---|---|---|
| Mean (m/s) | 1.715 | 2.74 | 2.534 | 1.89 | 1.888 | 2.675 | 2.7 | 2.46 |
| Number of data points | 563 | 703 | 377 | 156 | 151 | 204 | 380 | 444 |
| Wind direction | 180 (S) | 202.5 | 225 (SW) | 247.5 | 270 (W) | 292.5 | 315 (NW) | 337.5 |
| Mean (m/s) | 2.35 | 2.29 | 2.187 | 1.965 | 1.975 | 1.592 | 1.304 | 1.396 |
| Number of data points | 796 | 806 | 427 | 238 | 311 | 376 | 448 | 577 |

values, 0.12, 0.24, 0.3, and 0.36, are investigated for each orientation. Horizontal shading device lengths of 0 (no shading), 300 and 600 mm are investigated for north and south orientation facades and device lengths of 0, 600 and 1200 mm are investigated for east and west orientation facades. The window to wall ratio for the kitchen is taken to be the same as the one in living room when it is equal to 0.12, 0.24, and 0.3. When the window to wall ratio is equal to 0.36 for the living room, the window to wall ratio for kitchen remains to be 0.3. Thermal conductivity 1.89 W/m$^2$ K is chosen to be the thermal property of external hollow block wall.

Therefore, eight typical weather conditions (typical hours) are built up and set into weather data files. For each case, coupled simulations are executed for these typical hours.

### 3.4. Coupled simulation results

#### 3.4.1. Indoor air velocity results

The main parameter affecting indoor air velocity is window sizes, which is expressed as WWR (window to wall ratios) in the study. Four different WWR values, 0.12, 0.24, 0.3 and 0.36 are investigated for cross ventilation. The window sizes are 1.2 m × 1.2 m (WXH) for both sides (WWR = 0.12), 2.4 m × 1.2 m for both sides (WWR = 0.24), 3 m × 1.2 m (WWR = 0.3) for both sides, and 3.6 m × 1.2 m for one side, which is consistent with facade orientation and 3 m × 1.2 m for the other side, which is in the opposite orientation (WWR = 0.36). As shown in Fig. 12, when the wind direction is strictly parallel to opening orientation, very little wind can be induced into the room. However, the wind speed is largely increased when wind direction is oblique to the openings (Fig. 13). Another interesting result, which is rather counter intuitive, is that with the increase of window to wall ratios, indoor air velocities are not always increased. When WWR is increased from 0.3 to 0.36, indoor air velocities are either increased or decreased depending on wind directions and facade orientations. For example, in the north wind direction (Fig. 12), when facade is north facing (inlet window size is larger than outlet size), the indoor air velocity is decreased as the WWR is increased to 0.36, but when the facade is south facing (inlet window size is smaller than outlet size), the indoor air velocity is increased as the WWR is increased to 0.36. Similar results can be observed for other wind directions, either normal or oblique to openings. It can be concluded from the results that large outlet window size can promote higher wind speed, which is consistent with the other studies [8]. When the inlet size is the same as outlet size, with the increase of WWR, the indoor air velocity are increased.

However, for the naturally ventilated buildings in order to provide comfortable indoor thermal environment, it would be biased to particularly pursing high indoor air velocity as there is the risk that with the increase of fenestration sizes, the increase of solar heat gains and heat exchange with outdoor environment can results in thermal discomfort. Therefore, the facade design criteria for natural ventilation, thermal comfort, should be clearly taken into consideration to give a comprehensive evaluation on indoor environment.

#### 3.4.2. Thermal comfort distribution

Thermal comfort index for the eight wind directions were predicted based on coupled simulation results. The main wind directions (north and south) for Singapore are analyzed.

*3.4.2.1. North wind direction.* The best facade design for north wind direction is WWR = 0.36, south facing and with horizontal shading width 300 mm above. The optimum facade designs for each orientation are listed in Table 2.

*The impact of orientation*. When data are sorted based on thermal comfort, thermal comfort index are automatically sorted by orientations. Fig. 14 shows thermal comfort

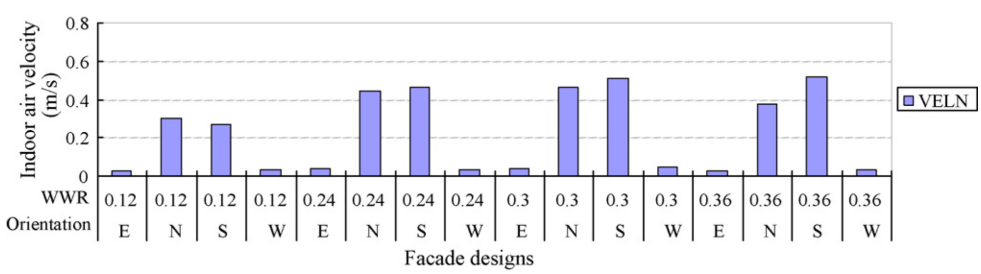


Fig. 12. Averaged indoor air velocity with wind direction from north for various designs.

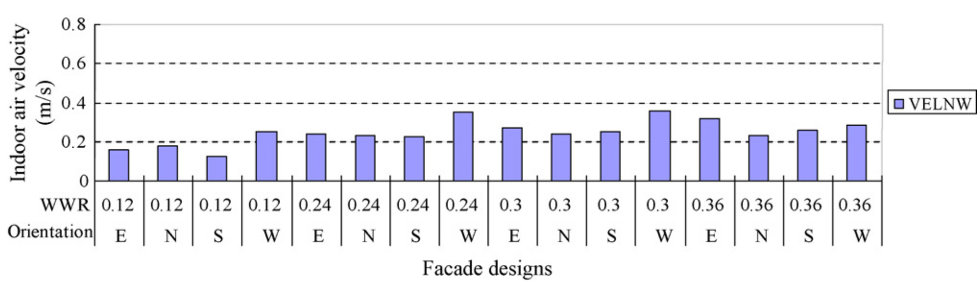


Fig. 13. Averaged indoor air velocity with wind direction from north west for various facade design.

Table 2
Optimum facade designs for N S W E orientations with north wind

| Orientation | Optimum WWR | Optimum shading (horizontal) |
|---|---|---|
| N | 0.36 | 300 mm above |
| S | 0.24 | With or without shading |
| W | 0.12 | 1200 mm above |
| E | 0.12 or 0.24 | 1200 mm above |

Table 3
Optimum facade design for N S W E orientations with south wind

| Orientation | Optimum WWR | Optimum shading (horizontal) |
|---|---|---|
| N | 0.36 | With or without shading |
| S | 0.24 | With or without shading |
| W | 0.24 | 1200 mm above |
| E | 0.12 or 0.24 | 1200 mm above |

distribution of eight cases (composed of maximum and minimum PMV cases for each facade orientation) for north wind direction. Generally speaking, north and south facing facades can provide much better thermal comfort than west and east facing facades and thus should be considered as priority. For the same WWR ratio and shading device, the largest difference in the thermal comfort provided due to orientation is from 0.51 (WWR 0.36, 600 mm shading device, north) to 1.13 (WWR 0.36, 600 mm shading, east).

*The impact of WWR (window to wall ratio) and shading devices*. In addition to the facade orientation, WWR and shading devices are also significant parameters in facade design. As can be seen in Table 2, the optimum WWR and shading dimensions vary according to different facade orientations. For south facing facade, the optimum facade design is WWR = 0.36 with horizontal shading width more than 300 mm. For north facing facade, the optimum WWR is 0.24 with or without shading. For west facing facade the optimum WWR is 0.12 with horizontal shading width more than 1200 mm and for east facing facade the optimum WWR is 0.24 or 0.12 with horizontal shading width more than 1200 mm. Since west and east are the worst facing scenarios, facade design in west and east facades should be paid more attention. It can be seen in Fig. 14, thermal comfort index increases from 0.772 (optimum facade design) to 0.95 (worst facade design) with west facing facade and it increases from 0.95 (optimum facade design) to 1.26 (worst facade design) in east facing facade. Shading devices are needed for the west and east facing facade to improve indoor thermal comfort. For west and east orientations, if local main wind direction is mainly parallel with the facade, large WWR should be avoided even for the naturally ventilated buildings, which results in more solar heat gains, higher surface temperature and higher indoor temperature.

*3.4.2.2. South wind direction.* The best facade design for south wind direction is WWR = 0.36, north facing and without shading devices. The optimum facade designs for each orientation are listed in Table 3.

*The impact of orientation*. Same as the results from north wind direction, north and south facing facades can provide much better thermal comfort than west and east facing when winds come from south. Fig. 15 illustrates thermal comfort distribution of eight cases (composed of maximum and minimum PMV cases for each facade orientation) for south wind direction. For the same WWR ratio and shading device, the largest difference for thermal comfort provided due to orientation is from 0.41 to 1.29.

*The impact of WWR (window to wall ratio) and shading devices*. As shown in Table 3, the optimum WWR and shading dimensions vary according to different facade orientations. For south facing facade, WWR 0.24 with or without horizontal shading is preferred, for north facing facade choose 0.36 with or without shading, for west facing facade, WWR 0.24 with horizontal shading width more than 1200 mm is preferred and for east facing facade, WWR 0.12 or 0.24 with horizontal shading width more than 1200 mm is preferred. West and east orientations are the worst facing scenarios when winds come from south direction. As can be seen in Fig. 15, thermal comfort index increases from 1.06 (optimum facade design) to 1.29 (worst facade design) with west facing facade and it increases from 0.86 (optimum facade design) to 1.2 (worst facade design) in east facing facade. Shading devices are highly needed for the west and east facing facade to improve indoor thermal comfort. For west and east orientations, when wind direction is parallel with the facade, large WWR should be avoided.

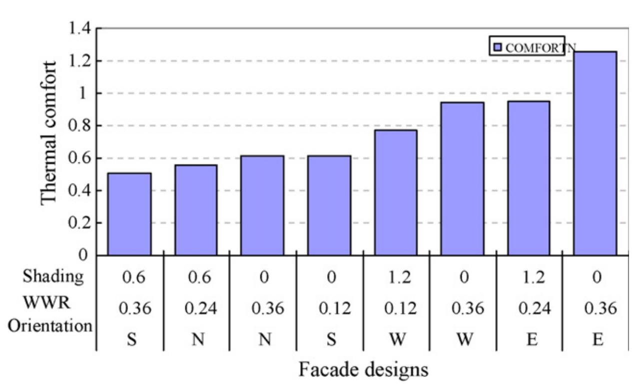


Fig. 14. Thermal comfort index of various facade designs with wind direction from north.

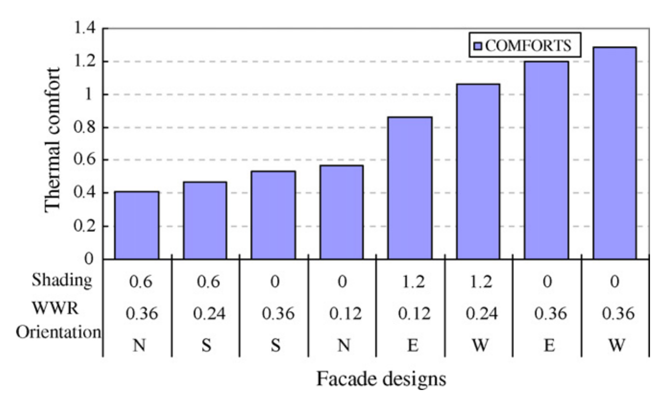


Fig. 15. Thermal comfort index of various facade designs with wind direction from south.

Table 4
Design guidelines for naturally ventilation residential buildings in Singapore

| | East | West | North | South |
|---|---|---|---|---|
| WWR = 0.12 | $U = 2$ W/m$^2$ K, PMV = 0.82, above 600 mm horizontal shading | $U = 2$W/m$^2$ K, PMV = 0.83, above 600 mm horizontal shading | $U = 2.5$ W/m$^2$ K, PMV = 0.59, no shading is needed | $U = 2.5$ W/m$^2$ K, PMV = 0.58, no shading is needed |
| WWR = 0.24 | $U = 2$W/m$^2$ K, PMV = 0.75, above 600 mm horizontal shading | $U = 2$ W/m$^2$ K, PMV = 0.77, 600 mm horizontal shading is needed | $U = 2.5$ W/m$^2$ K, PMV = 0.54, 300 mm horizontal shading is needed | $U = 2.5$ W/m$^2$ K, PMV = 0.53, 300 mm horizontal shading is needed |
| WWR = 0.3 | $U = 2$ W/m$^2$ K, PMV = 0.75, above 1200 mm horizontal shading | $U = 2$ W/m$^2$ K, PMV = 0.78, above 1200 mm horizontal shading | $U = 2.5$ W/m$^2$ K, PMV = 0.54, 300 mm horizontal shading | $U = 2.5$ W/m$^2$ K, PMV = 0.54, 300 mm horizontal shading |
| WWR = 0.36 | $U = 2$ W/m$^2$ K, PMV = 0.81, above 1200 mm horizontal shading | $U = 2$ W/m$^2$ K, PMV = 0.83, above 1200 mm horizontal shading | $U = 2.5$ W/m$^2$ K, PMV = 0.56, 300 mm horizontal shading | $U = 2.5$ W/m$^2$ K, PMV = 0.56, 300 mm horizontal shading |

## 4. Design guidelines

The following results can be drawn based on the above investigations of natural ventilation in Singapore.

(1) The $U$-value of facade materials for north and south orientation should be less than 2.5 W/m$^2$ K and the $U$-value of facade materials for north and south orientation should be less than 2 W/m$^2$ K in order to avoid thermal asymmetry near the openings.
(2) North and south facing facades can provide much comfortable indoor environment than east and west facing facades in Singapore. Shading devices are needed for east and west facing facades.
(3) If residential buildings have to face east or west due to the site limitations, try to build up buildings in such a way that they are about 45° to the west or east to increase ventilation. Direct east and west facing facades should be avoided.
(4) The coupled simulations indicate the optimum window to wall ratio is equal to 0.24. Horizontal shading devices are needed for the four orientations for further improvement in indoor thermal comfort. In the future studies, other shade devices like vertical fins or the combination of both vertical fins and horizontal shading devices could be investigated on west and east facing facade in order to provide better indoor thermal comfort.
(5) Based on the coupled simulation results of eight typical hours, the weighted thermal comfort index results with acceptable $U$ values are summarized in Table 4.

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